LA-UR-04-3192

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Submitted to: Proceedings of ICAPP '04
Pittsburgh, PA USA
June 13 - 17, 2004

Technical Bases to Consider for Performance and Demonstration Testing of Space Fission Reactors

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Abstract – *Performance and demonstration testing are critical to the success of a space fission reactor program. However, the type and extent to which testing of space reactors should be performed has been a point of discussion within the industry for many years. With regard to full power ground nuclear tests, questions such as 'Do the benefits outweigh the risks? Are there equivalent alternatives? Can a test facility be constructed (or modified) in a reasonable amount of time? Will the test article accurately represent the flight system? Are the costs too restrictive?' have been debated for decades. There are obvious benefits of full power ground nuclear testing such as obtaining systems integrated reliability data on a full-scale, complete end-to-end system. But these benefits come at some programmatic risk. In addition, this type of testing does not address safety related issues. This paper will discuss and assess these and other technical considerations essential in deciding which type of performance and demonstration testing to conduct on space fission reactor systems.*

I. INTRODUCTION

The result of any good engineering program is for the end product to perform as well as designed. This is accomplished by physically testing the item; testing is the only method that will provide nearly 100% certainty the physical item performs as designed. This holds true for space fission reactors as well. Until a prototypic unit is fabricated and realistic testing is conducted, the performance and operating characteristics of a reactor concept cannot be confirmed. Because of the long hiatus since the last US space reactor was flown and with the aggressive schedule President Bush has outlined for solar system exploration, it is imperative to demonstrate that space nuclear power and propulsion designs will perform as expected. There is no prescription for determining what types of tests are required. Each system will dictate the amount of nuclear testing required in reaching technical readiness. Ultimately it is up to the program sponsor to determine what types of tests are desired. The test data must be weighed against cost, utility, and timeliness to the program. Full power ground nuclear testing or combinations of nuclear and nonnuclear tests are options that can provide the sponsor with the level of certainty that the system under development will perform as designed. We will discuss past testing programs, recent and ongoing tests, and we will compare testing options available to aid program sponsors in deciding which tests will meet the needs of their programs.

There is a long history of testing space nuclear reactors in this country and in the former Soviet Union. These previous space reactor programs have generated an enormous amount of useful information, yet the US has flown only one space fission reactor. It is incumbent upon this generation of engineers to glean the knowledge gained and lessons learned from these past programs to enable current and future programs to fruition.

Testing of nuclear space systems began in the mid 1950's in the US with the Rover nuclear rocket program. The Rover program was a huge technological success, but due to changes in national priorities, the program was terminated before any flight demonstration could be made. The SNAP Program was a huge success. It was the program that launched and flew the only US space reactor, however, it too was terminated prematurely. The SP-100 program spent nearly a quarter of a billion (then) dollars developing a full power ground nuclear test before the program was scrubbed. The TOPAZ reactors, developed by the former Soviet Union (FSU) became an international program in the early 1990s when the US purchased several TOPAZ II reactor power systems. This program consisted of an extensive series of nonnuclear ground tests aimed at understanding the capabilities and limitations of the FSU TOPAZ II thermionic system. These programs had extensive reactor testing programs, yet in the 30 years since the end of the SNAP program, no full power ground nuclear tests have been conducted in the US.

II. TESTING OBJECTIVES

First and foremost in the development of any space fission program is the concern for safety. For many reasons, a reactor program will only be considered feasible if the reactor can be built and operated without harm to people or the environment. Therefore, space fission testing programs address not only performance and functionality issues, but safety issues as well. This paper, however, does not address safety testing; we only discuss performance and operational testing.

Different tests have different values in helping convert paper reactor concepts into working space hardware. In addition, some space reactor concepts and approaches are significantly more easily tested than others. One method for assessing the value of a given test or test program is by its "test effectiveness." Test effectiveness is defined as the degree to which a test or test program helps lead to a successful mission application. Factors include the realism of the test conditions and how well the test article being tested represents the flight system, Houts *et al*[1]. Previous programs (e.g., SP-100) have applied the concept of test effectiveness in a similar fashion.

There are several different categories of tests normally required in a space reactor flight program. Developmental testing is conducted during the design phase of the project. Components and subsystems are developed during this phase and this is the phase of the project where parameters are optimized to meet differing criteria that will be encountered during the flight portion of the program. Engineering performance or demonstration tests are defined such that the functionality may be tested on the optimized components and subsystems and integrated system performance can be demonstrated. These tests often incorporate any off-normal or transient conditions, thus enabling modifications and refinements to the design before final incorporation into a flight system and thus ensuring the safety envelope is maintained. Engineering performance tests demonstrate the performance, reliability, lifetime, manufacturing capability, and safety of the reactor system. Qualification tests are the most rigorous tests the system will undergo. These tests ensure the subsystems will perform up to their design limits. For example, these tests may include vibration and structural tests to ensure the system will survive launch, and that criticality can be demonstrated under a variety of transient scenarios. These types of tests are typically conducted at conditions more severe than is expected *in situ*. Acceptance tests are the final series of tests that represent, as prototypically as possible, the final flight system. These tests are conducted just prior to flight to ensure the flight units are built as qualified.

III. HISTORICAL PERSPECTIVE

The prospect of nuclear power in space began in May of 1946 when a contract was formed between the Army Air Force and Fairchild to study nuclear energy for the propulsion of aircraft. In 1953, Los Alamos Scientific Laboratory was chartered to conduct a nuclear rocket study. The recommendation of that study was to use nuclear propulsion on ICBMs, and 1955 marked the beginning of reactors in space with the Rover nuclear rocket program. What follows is a brief description of the testing programs from the larger space reactor programs of the past.

III.A. Nuclear Rocket (Rover) Test Program

The approach taken by the Rover nuclear rocket program was to heat a propellant in a reactor to a very high temperature (2500 K) and expand the heated gas through a nozzle to obtain directional thrust, Spence.[2] The motivation behind the nuclear rocket was that it could provide about twice the specific impulse of the best chemical rocket of the time, Koenig.[3] The Rover program was terminated in 1973 at the point of flight engine development, but testing indicated no technological barriers existed to a successful flight system. Over the course of the program, applications for its use changed from being a backup for ICBMs to functioning as the second stage for lunar flight to being used in manned mars flights and finally discussions were made for their use in orbit-to-orbit transfer. When analysis showed that chemical rockets were more economical and mission applications did not substantiate the use of nuclear rockets, the use of a nuclear engine for rocket vehicle application (NERVA) was no longer pursued and the program was terminated before a flight demonstration could be made. Even so, the program was judged to be a technical success and a plethora of information was gained on the design and demonstration of nuclear fission reactors.

A series of reactors and engines were built and tested at the Nuclear Rocket Development Station at Jackass Flats at the Nevada Test Site (Figure 1). The testing program was initiated with a series of research reactors called Kiwi (after the flightless bird of New Zealand). The program objectives of the Kiwi reactor series was to demonstrate proof of principle and establish the basic reactor technology and design concepts. The Kiwi reactors were the first to demonstrate the use of high-temperature fuels and to operate with liquid hydrogen. The Kiwi tests led to the development of the Nuclear Reactor Experiment (NRX) series of developmental reactors. The goal of the NRX series was to demonstrate a specific impulse of 760 s (7450 m/s) for 60 min at a thrust level of 245 kN (55,000 lb in an 1100 MW reactor. These objectives were exceeded in the last test of the NRX series; the NRX-6 operated for 62 min at 1100 MW and a temperature of 2200 K, Koenig.[3] The Phoebus reactor series was also developed under the Rover program. The objectives of the Phoebus series was to increase the specific impulse to 825 s, increase the power density by 50%, and increase the power level to the 4000-5000 MW range. These capabilities were also exceeded and the Phoebus 2A reactor was the most powerful reactor ever built. It ran for 12 min at 4000 MW and reached a peak power of 4080 MW. The last two series of research reactors from the Rover program were the Pewee and the Nuclear Furnace. These series were each tested only once and were lower power reactors designed primarily as test beds to demonstrate the capabilities of higher-temperature fuel elements.

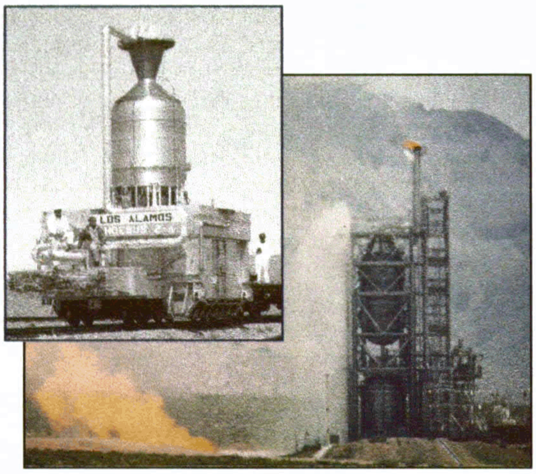

Figure 1. Rover program NTR test cell; inset: Phoebus 2A reactor en route to test cell.

An engine development test program was part of the technology demonstration for Rover. Its objectives were to test the nonnuclear system components; determine system characteristics during startup, full power, and shutdown conditions; evaluate control concepts; and qualify the engine test-stand operations with simulated altitude and space conditions. These objectives were met or exceeded in the Nuclear Reactor Experiment/Engine System Test (NRX/EST) and Experimental Engine (XE) programs. A prototype flight engine system, XE, consisting of a flight-type reactor with nonnuclear flight components was tested in a space-simulated environment, performing numerous (28) starts and restarts. It was recognized during this program that a nuclear rocket engine could be altered so that it could also provide power to mission payloads. Design studies for such bimodal rocket systems were begun in 1971-72 where one mode was the normal propulsion system and the second mode was a closed-loop, low-power electrical system. The program was terminated shortly thereafter at the point of flight engine development.

III.B. System for Nuclear Auxiliary Power (SNAP) Test Program

Only one US reactor has ever flown in space–the SNAP 10A reactor. In April 1965, SNAP 10A, FS-4 was launched into a 750 mi (1250 km) orbit. The FS-4 system started in orbit at 500 W_e. An experiment to test cesium ion engines was added late in the flight demonstration program, and after 43 days of operation in orbit, the ion engine was started up. A spike in electrical potential from a faulty voltage regulator on the spacecraft caused the reactor to shut down prematurely. The SNAP 10A FS-4 has been the only US space fission reactor flown to date. Earlier in 1965, the SNAP 10A, FS-3 began a 1-year full power, ground nuclear qualification test. It operated in a vacuum with no active control for 10,000 h.

The SNAP 10A system development was directed primarily toward (1) early identification of basic system information essential to the design of the flight system (Figure 2) and (2) demonstration and qualification of the flight systems. The first objective was achieved by two structural tests (PSM-1 and -1a) and an early thermal test unit (PSM-3). The second objective was achieved by testing two full scale nonnuclear systems (FSM-1 and -4) and one nuclear flight (FS-3) system.

The prototype system mockups underwent nonnuclear tests to determine the response of the structure to the acceleration, shock and vibration forces anticipated during launch and orbital placement. PSM-1a, was a modified version of PSM-1. The test was duplicated to ensure the design changes corrected previous deficiencies. PSM-3 was used for the first thermal test on a prototype system to investigate the thermal, hydraulic, and heat transfer characteristics system design. Solar orbital and space sink temperatures were also simulated to observe thermal response to the space environment. This test was plagued by electric core heater failure at full operating temperature and power, but in all tests, the results substantiated the basic design parameters, Schmidt.[4]

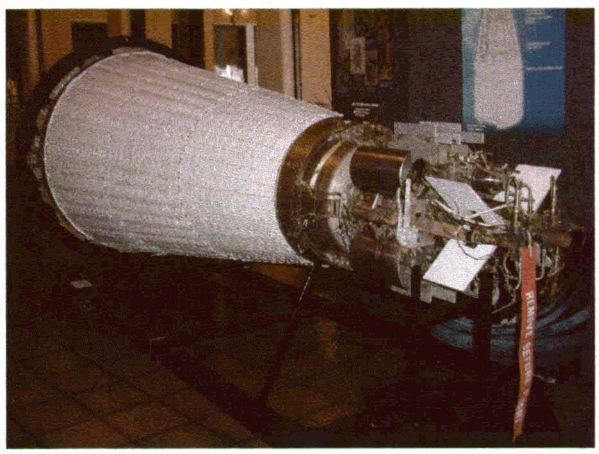

Figure 2. SNAP 10A reactor-backup unit.

The first full-scale, nonnuclear flight system, FSM-1, tested at design temperatures for 90 days. The pre-operational checkout, performed at ambient environment conditions, verified the electrical integrity of the final assembly. Subsystem operation was checked by sending commands to simulate various phases of the flight. Verification of successful operation was monitored through special test points and visual inspection. Shock and vibration tests were performed at the acceptance and qualification levels. Several discrepancies were observed during acceptance tests and corrected prior to the start of qualification tests. The most common faults that occurred were simple things like loose nuts vibrating off, wires fraying and micro-switches cracking. These discrepancies were all corrected by redesign for the flight system. Flight System Mockup-4 was used to demonstrate and qualify the factory-through-orbital operations. Major differences between this and FSM-1 were in the thermoelectric converter, NaK pump, expansion compensators, and instrumentation. This system test confirmed the earlier system test results, which demonstrated compatibility among components integrated into a system and low temperature performance during simulated orbit prestart conditions. An additional 15 tests were completed during a nine month period to ensure compatibility with the Agena launch vehicle. The electrical mockup (FSEM-2A) had electrical and instrumentation characteristics similar to the flight system, such as radiation shield mockup, reactor core mass mockup, and a thermoelectric pump (from qualification testing).

The principal objective of the nuclear qualification test program, using FS-3, was to demonstrate that the SNAP 10A system would fulfill the design performance requirements. The acceptance test program included major tests such as shock and vibration (acceptance and qualification levels), fuel loading and dry critical determinations, NaK coolant filling and purification, thermal acceptance, and nuclear acceptance. On January 22, 1965, the automatic startup of the system to design conditions was achieved. The FS-3 system was shut down on March 15, 1966. The FS-3 nuclear qualification test had accumulated 10,000 hours at design temperature and full power. To enable performance of the nuclear qualification test, modifications to the flight system were necessary. Some of these modifications included: the reactor controller was located outside the power test cell and an identical controller was installed in the instrument compartment; a neutron source was installed to simulate the neutron source in space; and the reflector assembly was modified to permit remote removal of the reflectors.

The flight test of FS-4 culminated the design, development, qualification, and demonstration of the SNAP 10A nuclear reactor power system for space applications. All testing performed prior to launch indicated a high level of system readiness. A rigorous review was made of the information obtained from the flight test demonstration and it was concluded that most of the flight test goals and objectives were met and that a space nuclear power system can be launched, started, and operated safely in space. It should also be noted that in addition to the success of SNAP-10A reactor, the SNAP reactor program resulted in extensive testing of alternative reactor concepts as well as an exhaustive safety test program.

III.C. SP-100 Test Program

In the early 1980s, the Strategic Defense Initiative Office was pursuing space-based defensive systems in the power range of 100 kW_e. NASA was also looking at space reactor power systems with similar power ratings for use in missions to the outer planets. The SP-100 program was started in FY 1983 to determine if a space reactor power system could be developed to satisfy both military and civilian requirements for future space missions. The basic requirements for such a power system at that time were: power output of 50 to 1000 kW_e, seven year full power lifetime, ten year mission lifetime, and 3000 kg mass at 100 kW_e. The thermal energy generated by the reactor was to be transformed to electrical energy by passive thermoelectric devices and the excess heat was to be radiated to space via potassium filled heat pipes radiators. See Figure 3 for a drawing of the SP-100 spacecraft.

The SP-100 program was organized into three phases. Phase I of the program determined the technical and safety feasibility of the system concept. As a result of the three-year Phase 1 effort, the Program/Project Office and the tri-agency (DOE, DoD, NASA) Steering Committee selected a space reactor power system that used a uranium nitride fueled, lithium cooled, fast-spectrum reactor to produce heat and thermoelectrics for converting that heat to electricity. Phase II, or the Ground Engineering System (GES), was the developmental stage of the program. The objective of Phase II was to provide the engineering data base and the analytical design tools that were needed to design, fabricate, and qualify a ten-year, low-mass space reactor power system for use in a specific future military or civilian mission within a 10 to 300 kW_e power range, and consisted of design and development of components and subsystems of the reactor and auxiliary systems, Jeanmougin, Moore and Wait.[5] The system was to be developed within 5 years. Unfortunately, the program was cancelled before Phase III could be completed, which was the flight system demonstration and qualification testing phase of the program. The original plan was to test the reactor and its subsystems separately from the balance of the spacecraft. The two tests, named the Nuclear Assembly Test (NAT) and the Integrated Assembly Test (IAT) were never carried out.

The GES was a compilation of many tasks, directed toward developing and validating the technology necessary for a flight system with a power level anywhere between 10 kW_e and 300 kW_e. This approach required a validation plan that covered all components and interfaces so that when completed, the results of the SP-100 project would be able to quantitatively and convincingly validate that the technology was ready for a space mission without building and testing a complete ground system. Initially, the program plan was to build and ground-test the reactor, shield, and reactor instrumentation and control subsystems at the full thermal power rating required for the 100 kW_e thermoelectric space power system. Preparing for the NAT was very valuable in developing the technology for the flight nuclear subsystems. Based on this newly acquired technology, it was decided and agreed to by all program participants that actually conducting the NAT was too expensive for its incremental value in validating the nuclear subsystems technology for a flight system. Therefore, testing of a nuclear assembly on the ground was deleted from the SP-100 program technology development plans, Buksa *et al.*[6]

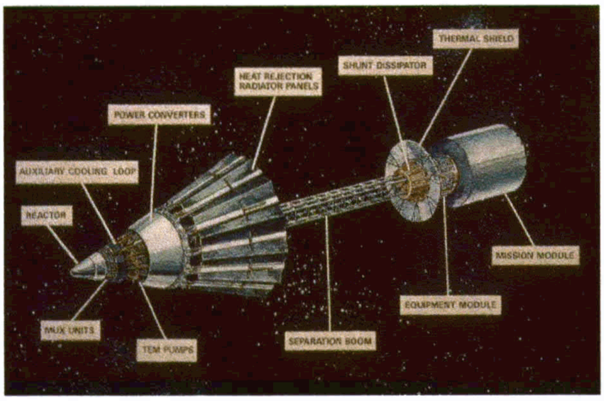

Figure 3. Artist's rendering of the SP-100 space reactor.

Another part of the SP-100 project that was to be a major contributor to validating the system was a reliability and lifetime task. This task used analyses verified by experimental results to show design margins for all postulated failure mechanisms within the system. Potential failure mechanisms were identified and analytically described. At completion, the analytical description of the failure mechanisms were to be verified by either existing experimental data or experimental data developed under the SP-100 project. The results of the failure mechanism analyses and experimental verification were to be reported in Design Margin Reports. When completed, the reports would describe the mechanism, the analytical predictions, the experimental data, the operating conditions, and the margin to failure in the number of years in excess of the requirement. Some of the identified failure mechanisms went through this entire process.

An electrically heated system ground test was planned (but not implemented) which would test the complete reactor and shield subsystems and operating prototype modules of a portion of the other six subsystems, with thermal/mass mockups modules for the remainder of the six subsystems. This system test would have validated that all the subsystems would interface properly and operate together as a system. After the electrically heated test, the reactor then would have been fueled and a warm and a cold zero power critical test would have been performed to validate the reactor just before flight. These tests were designed to satisfy requirements for a qualified flight power system. Because of schedule slips and the premature termination of the project, these tasks were not completed.

III.D. TOPAZ Test Program

In 1991, the US purchased 2 fully operational TOPAZ-II units (V-71 and Ya-21U), 2 engineering mockup units (no fuel and no NaK), and 2 flight systems from the former Soviet Union. The TOPAZ International Program (TIP) was an extensive series of nonnuclear ground tests aimed at: (1) understanding the capabilities and limitations of the TOPAZ-II thermionic system, (2) conducting basic research with an international team of thermionic and materials experts, and (3) assessing critical component design for increased power generation (the 40kW program). The TOPAZ program was terminated in 1996.

The original TOPAZ-II system test program required specific tests to be performed on each of the 6 available articles. Information and technology obtained from the initial system tests would be applied directly to future system tests. The actual tests performed on the Ya-21U included a modal test, 8 thermal vacuum performance tests, a set of mechanical vibration and shock tests, and 5 final, post-mechanical thermal vacuum system performance tests. These actual tests accommodated unanticipated problems encountered with the TSET facility's uninterruptible power supply system and the Baikal test stand equipment and permitted more comprehensive evaluations of the system's performance and durability, Schmidt.[7]

The Ya-21U system (see Figure 4) was a compact space nuclear power system based on thermionic power conversion. Major functional subsystems of the TOPAZ-II system included: a nuclear reactor that contained the enriched fuel, moderator and thermionic converters; a radiation shield; a NaK coolant system; a cesium supply system; gas supply systems; a startup unit and battery; support structures; instrumentation sensors; a reactor control and monitoring system; an automatic control system; and a segmented thermal cover. The reactor was designed to provide 115-135 kW_e of thermal energy to 37 thermionic converter fuel elements (TFEs) during ground nuclear tests and planned flight demonstration tests.

The TOPAZ-II system design had 3 significant features that enhanced testability, transportation, storage, safety, and security of enriched nuclear fuels: (1) the design of the single cell TFEs permitted the reactor fuel to be installed and removed easily during subcritical and zero power nuclear testing and transportation between facilities, (2) the TFE design permitted electric heaters to be inserted in place of the nuclear fuel and enabled system testing at operating temperatures and power levels in a nonnuclear test facility, and (3) the cesium system design permitted optimization of the cesium pressure during acceptance testing for each TOPAZ-II system, Schmidt.[7]

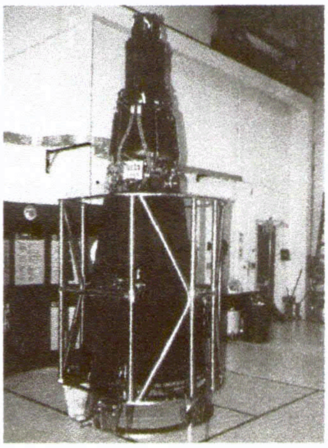

Figure 4. Photograph of a TOPAZ-II reactor.

In 1993, Ya-21U was operated at temperature for more than 1000 hr in the Baikal test stand thermal vacuum chamber at the TSET Laboratory. This test was used to evaluate the reactor's performance at operating conditions, to obtain data for design of system modifications, and to determine the response of the system to external inputs. The test also provided operational performance data to support the previously planned flight demonstration.

IV. RECENT TESTING ON SPACE REACTORS

Within the past few years, NASA Marshall Space Flight Center developed a facility to enable testing of reactor systems without the use of nuclear fuel. Electrical resistance heaters used in the Early Fission Flight Test Facility (EFF-TF) simulate the thermal heat generated from nuclear fission. Thermal simulators have been developed over the past five years that would enable highly realistic non-nuclear testing of systems currently under consideration, and eliminate lifetime and reliabililty concerns that were encountered with the electric heaters of the SNAP 10A program. Successful tests have been conducted in this facility on components and at the integrated subsystem level. A direct drive gas cooled reactor core has been fabricated and initial testing of a core segment completed at the EFF-TF. Extensive work related to heat pipe cooled reactor concepts has also been performed. Work associated with pumped alkali metal systems has been initiated. A full description of the EFF-TF can be found in Van Dyke.[8]

IV.A. Heat Pipe Reactor Demonstration

Heat pipe cooled systems were the first to undergo hardware-based technology assessment at the EFF-TF. In this type of prototype reactor, thermal heat is transferred from the fuel elements via heat pipes to a heat exchanger and then to a power conversion system. Fabrication and initial testing of a full core, 30 kW_t system in 2000, provided information concerning the potential operation of a full reactor core. A Stirling engine was coupled to the core and both steady state and transient tests were performed. Upon completion of the coupled reactor core/power conversion system tests, the system was sent to the Jet Propulsion Laboratory where it was integrated with an ion thruster (see Figure 5) and tested for several months. Further details of the SAFE 30 test series can be found in Van Dyke[9] and Hrbud.[10]

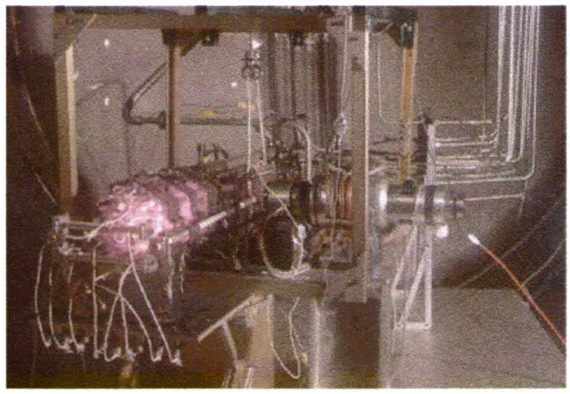

Figure 5. Electrically heated demonstration of a heat pipe reactor/Stirling engine coupled to an ion thruster.

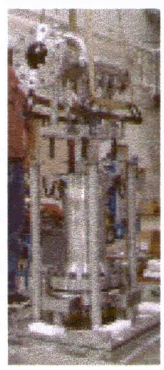

Figure 6. Direct drive gas cooled reactor being prepared for electrically heated demonstration.

IV.B. Direct Drive Gas-cooled Reactor Initial Testing

A direct drive gas-cooled reactor coupled to a Brayton power conversion system is currently being testing at the EFF-TF (see Figure 6). In this type of reactor, power is transferred from the reactor to the Brayton system via a circulated closed loop gas; the gas drives the turbomachinery without requiring a separate heat exchanger. In order to make the most efficient use of time and funds, nitrogen was used as the working fluid in place of the expensive HeXe gas for the initial testing. Preliminary tests indicate that the test article is performing as expected and the primary objective of engineering a nonnuclear test of a direct drive gas-cooled reactor has been successfully completed, Godfroy *et al.*[11]

V. System Testing Options

For demonstration and performance testing, three types of tests will be compared: (1) full power ground nuclear test – the testing of a complete reactor system where heat is generated by fission in a prototypic flight system, (2) zero power nuclear tests – neutronic testing of various operational characteristics of a fission reactor, where such testing may include prolonged operations at steady-state or transient thermal conditions yet leaves the reactor and components essentially non-radioactive, and (3) nonnuclear tests – testing using electric heaters to simulate the heat from fission reaction. Table 1 lists the main reactor subsystems, objectives for each subsystem test, and under which test type these objectives may be obtained. Component development tests are not included here because it is assumed that this type of testing is a normal part of the development process. For example, fuel qualification tests are not listed because it is assumed the fuel would have passed qualification stage for it to be included in the nuclear tests listed in the table.

V.A. Full Power Ground Nuclear System Tests

At a superficial level, full power ground nuclear testing would appear to be the most obvious method for demonstrating a complete space reactor system. However, the effectiveness of full power ground nuclear testing is limited by how well the system being tested represents the flight system and the effects of test facility requirements on test operation. For example, significant reactor design modifications are required to for the system to meet facility safety and operational requirements. These potentially include the addition of redundant and diverse shutdown mechanisms to the core that would not be present in the flight unit. The facility could also affect the validity of nuclear testing because of non-prototypic radiation scatter.

Advantages (1) Testing is performed on a complete end-to-end system; this increases the confidence in the performance of a flight system. (2) Design temperature and full power can be ascertained.

Disadvantages (1) Test article may not accurately represent the flight system because of the additional facility and safety requirements. (2) Components may not be analyzed until the test is complete; this could lead to delays in modification and optimization and potential program delays. (3) Radiation-resistant instrumentation (temperature, strain, pressure) would be required, potentially limiting the amount of data that could be obtained; replacing failed instrumentation would require a significant, remote operation. (4) Over-testing and test-to-failure are not be feasible. (5) No operational facility currently exists where these tests could be performed. (6) Highly valuable fresh fuel would become irradiated and would not be reuseable for a flight system. (7) Licensing of a new or modified facility will take months to years to accomplish. (8) Does not provide safety data, only data related to performance and (potentially) reliability.

V.B. Nonnuclear System Tests

Nonnuclear testing allows for a rigorous and thorough test plan and is flexible with regard to configuration and facilities. At power levels <400 kW_t, reactor systems can be designed such that the most potential issues are thermal or stress related; nuclear effects being considered secondary, Van Dyke *et al.*[12] Facilities such as the EFF-TF described earlier allow for components and subsystems to be designed, fabricated, and tested quickly and affordably using resistance heaters to simulate the thermal heat from nuclear fission. It may even be possible to obtain higher fidelity information related to heat transfer, temperature distribution, pressure, strain, bulk deformation, and potentially other parameters from a well-instrumented, highly realistic nonnuclear test than from a less-than-prototypic nuclear test, Houts *et al.*[1]

Advantages (1) Testing performed on subsystems and complete system *sans* enriched fuel. (2) Because radiation is not generated, test articles may be modified or swapped out relatively easily and timely. (3) Test duration may be long or short, depending on need. (4) The cause of component and system failure can be quickly and accurately identified and corrected. (5) Extensive temperature, pressure, strain, and bulk deformation measurements (to help predict reactivity feedback) can be made. (6) Allows for flexibility in testing, including margin testing and test to failure. (7) Expense and schedule impacts are reduced from facility and environmental considerations. (8) Provides potential reliability and safety data. (9) Large vacuum chamber facilities currently exist that can be used for nonnuclear tests (i.e., Plum Brook Station)

Disadvantages (1) Radiation damage to components not evaluated. (2) Control system not tested. (3) Nuclear design not verified. (4) Care must be taken to ensure thermal simulators do not contaminate the flight unit.

V.C. Zero Power Nuclear Tests

Zero-power critical experiments may be an effective way to verify the operational characteristics of a space reactor. In these experiments a self-sustaining fission chain reaction is maintained at a low power level to preclude generation of significant fission products. Zero power critical experiments can be performed in a range of temperatures and with various temperature profiles to obtain data on reactivity coefficients and reactor behavior during various steady-state and transient conditions. Electric induction heaters can be used to simulate operating temperatures while the reactor power output is maintained at extremely low levels, thus eliminating the concern of generating fission product inventory. Licensed operating facilities exist within the DOE/NNSA Complex where these types of tests could be performed.

Advantages (1) Reactivity feedback effects may be determined without irradiating the test article. (2) Neutronic performance can be demonstrated at low power. (3) Highly valuable fresh fuel would not become irradiated and would be reuseable for a flight system. (4) Performance of the closed loop digital control system can be tested and optimized in a non-irradiation environment.

Disadvantages (1) Tests in these experiments may not be conducted at full power in order to keep the fission product inventory negligible. (2) Only postulated anomalous conditions can be tested. (3) Modifications to the test unit may be required to satisfy facility requirements.

TABLE 1. Full system component and subsystem tests.

Component or Subsystem	Full Power Test	Zero Power Tests	Electrically Heated Tests	Objective
Fuel Performance	√	√		Measure neutronic performance
Fuel Pin Assembly	√*		√	Measure thermal/structural performance
Reactor Core and Subsystem	√	√	√	Test performance under normal and transient temperatures, reactivity feedback effects, power profile
Instrumentation & Control	√	√	√	Test functionality under variety of scenarios
Shield Subsystem	√		√	Determine structural, thermal integration
Heat Transport Subsystem	√		√	Verify heat transfer to primary heat exchanger
Power Conversion Subsystem	√		√	Test integration/operational behavior
Heat Rejection/Reflector Subsystem	√		√	Test performance under normal and transient conditions
Power Management Subsystem	√		√	Confirm predicted system feedback
Post Irradiation Examination	√*			Test radiation hardness of components
Thermal Performance of Prototype System	√		√	Test the thermal limits of the prototypic flight system
"Over Test" of Prototype System			√	Test the design limits of the prototypic flight system
Fully Deployed End-to-end Demonstration			√	Demonstrate integration of all subsystems;
Launch Safety Data		√		Verify predicted reactivity for postulated configurations, benchmark safety codes

*data not available until full power test is complete

VI. COSTS

Although not a technical concern, cost is integral to the testing decision and is therefore briefly addressed here. Reactor development costs have traditionally been very large. The Rover program costs were estimated at $1.4 billion (then-year dollars); the total SNAP Reactor Program spent over $880 million (then-year dollars); the SP-100 program spent more than $400 million in 1980 dollars; and the FSU spent the equivalent of $1 billion US (then-year dollars) in the development of the Topaz systems, Lee, Clement, and Hanrahan.[13]

Recent estimates for space reactor full power ground nuclear tests, including the test article, are on the order of one billion dollars. Excluding the test article, recent electrically heated tests have cost on the order of a few million dollars and zero-power critical tests are estimated to be in this range as well.

Cost-benefit analyses should be performed to determine if the potential increase in mission reliability or the potential to contribute to follow-on missions is justified by these costs. These tests cost the taxpayer millions of dollars. In today's atmosphere of highly constrained budgets, space fission programs must scrutinize the cost of testing more so now than ever before. Much was learned from previous developmental programs that can be applied to current and future space fission endeavors. It behooves current and future US space programs to capitalize on the lessons learned and technology gained from past experiences and incorporate new technology where technically and fiscally appropriate. It is incumbent upon us to determine the most cost effective means for reliability improvement.

VII. CONCLUSIONS

Because of the long hiatus since the last US space reactor was flown and with the aggressive schedule President Bush has outlined for solar system exploration, it is imperative to demonstrate that space nuclear power and propulsion designs will perform as expected. There is no prescription for determining what types of tests are required. Each system will dictate the amount of nuclear testing required in reaching technical readiness. Ultimately it is up to the program sponsor to determine what types of tests are desired for their particular programs. The test data must be weighed against cost, utility, and timeliness to the program. Full power ground nuclear testing or combinations of nuclear and nonnuclear tests are options that can provide the sponsor with the level of certainty that the system under development will perform as designed. This paper discussed past testing programs, recent and ongoing tests, and compared testing options available to aid program sponsors in deciding which tests will meet the needs of their programs. The authors hope the information provided in this paper will facilitate such decisions.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Glen Schmidt for his contributions regarding the SNAP and TOPAZ testing programs. In addition, we thank Dr. Thomas Godfroy for his input on the gas-cooled test at Marshall Space Flight Center. This work was funded by the Los Alamos National Laboratory and does not necessarily reflect the views of NASA's Project Prometheus, the Nuclear Systems Program.

NOMENCLATURE

FSM	-	flight system mockup
FSU	-	former Soviet Union
ICBM	-	intercontinental ballistic missile
PIE	-	post irradiation examination
PMAD	-	power management and distribution
PSM	-	prototype system mockup
TFE	-	thermionic converter fuel elements
TSET	-	thermionic systems evaluation test

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